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THEORY OF NON - LINEAR PLASMA WAVES IN THE FIELD EFFECT TRANSISTOR STRUCTURES.

FINAL TECHNICAL REPORT.

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ABSTRACT.

This report describes the results of the investigation of non - linear effects in the plasma oscillations in bounded electron systems. We studied an evolution of electron density distribution in the conduction channel of a Field Effect Transistor under various boundary conditions. It was shown that in a dynamically closed system the decay law of shock - like waves changes when different boundary conditions are imposed. We investigated the effects of plasma waves in the non - linear response of the conduction channel in FET structure. The effects of dissipation were included through the friction term in the Euler's equation of electronic fluid. The dependencies of the detector responsivity on the excitation level for different gate length, and electron mobilities was computed. We also studied the change of the wave form in the system with time independent boundary conditions when a small nonlinear dispersion term was included.

STATEMENT OF THE PROBLEM.

Recently M.I.Dyakonov and M.S.Shur [1] demonstrated that if the temperature is not too low, the two dimensional electrons in the channel of the Field Effect Transistor (FET) behave not as a gas (as conventionally expected) but as a fluid. As one can show, the electron mean free path for collisions with impurities and phonons is much greater than the mean free path for electron-electron collisions. This means that theoretical description of the electron flow in the FET channel should be based on the hydrodynamics equations [2]. Phenomena similar to the hydraulic jump observed in fluid and gas dynamics may be expected in such structures. Creation of shock waves, their propagation, reflection from the boundaries and damping should take place in electron fluid. All of this is of a significant interest in modeling and design of new electronic devices based on plasma oscillations [3, 4].

The purpose of this work is to investigate the non linear waves in electron fluid in a two - dimensional channel of FET structure, using a hydrodynamic description. We studied the strongly non linear regime of a plasma oscillations in quasi - two - dimensional systems with various boundary conditions. It is shown that if asymmetric boundary conditions are imposed on the source and drain contacts the linear plasmons become unstable and new non linear effects in the device response appear.

THEORETICAL APPROACH.

The theoretical approach is based on the non-linear hydrodynamic equations [2]. The principal partial differential equations are derived as mass, momentum, and energy balance equations. Application of these equations to the one - dimensional flow of the high density electron fluid in conduction channels of FETs was suggested in reference 1. Consider a narrow conduction channel of length L , separated by a distance d from the gate electrode. Let $n(r,t)$ and $v(r,t)$ be the 2D density and velocity of electrons in the channel, where r is 2D position vector in the (x,y) plane with the x axis chosen along the channel and the y axis across this one. In FETs the width of the conduction channel is much larger than the length and one - dimensional approach may be used. The flow is described by three balance equations which in the absence of viscosity can be written as follows:

$$\frac{\partial n}{\partial t} + \frac{\partial(nv)}{\partial x} = 0 \quad (1)$$

$$\frac{\partial(nv)}{\partial t} + \frac{\partial(nv^2)}{\partial x} + \frac{1}{m} \frac{\partial p}{\partial x} + \frac{en}{m} \frac{\partial U}{\partial x} + \frac{nv}{\tau} = 0 \quad (2)$$

$$\frac{\partial(nw)}{\partial t} + \frac{\partial}{\partial x}(nwv) + \frac{p}{m} \frac{\partial v}{\partial x} - \frac{nv^2}{\tau} = 0 \quad (3)$$

where $U(x,t)$ is the gate to channel voltage, p is the pressure defined here as a force per unit width, w is density of internal (thermodynamic) energy of the electron fluid, which is given in the equation of state as a function of p and n : $w = w(p,n)$, m is the electron effective mass, $-e$ is electron charge and τ is electron collision time with phonons and impurities. The relation between electron density fluctuation along the channel $\delta n(x,t)$ and the electric potential is determined by the three dimensional Poisson's equation.

$$\nabla^2 U = \frac{4\pi e}{\epsilon} \delta n \delta(z) \quad (4)$$

where ϵ is electrostatic constant, and $\delta(z)$ is the Dirac delta function. The time and space dependent 2D density may be written as $n(x,t) = n_0 + \delta n(x,t)$, where $n_0 = CU_0/e$ is the equilibrium density of electrons in the conduction channel, U_0 is the average gate voltage swing defined as the difference between gate-to-channel voltage and the threshold voltage, and C is the gate capacitance per unit area.

In our investigations we considered only such systems in which the contribution of the pressure gradient terms is small compared to the contribution of the self consistent electric field term. Then first two balance equations can be approximately decoupled from the internal energy balance equation.

When the scale of the electric potential variations in the channel is much greater than the gate to channel separation d , the solution of the Poisson's equation can be obtained self - consistently in the "gradual channel" approximation [1]:

$$U(x,t) = \frac{e}{C} n(x,t) \quad (5)$$

This approximation leads to a neglect of higher order terms in the dispersion law [5, 6], and momentum balance equation (2) may be rewritten in the following form:

$$\frac{\partial(nv)}{\partial t} + \frac{\partial(nv^2)}{\partial x} = -\frac{s_0^2}{2n_0} \frac{\partial n^2}{\partial x} - \frac{nv}{\tau} \quad (6)$$

Here $s_0 = (eU_0/m)^{1/2}$ is the plasmon velocity. The last term in eq.(6) describes a friction of electron fluid in conduction channel. The strength of the friction term is conveniently characterized by the dimensionless coefficient $\gamma = L/(s_0\tau)$.

For a continuous flow we can use equation (1) to obtain from (6) the Euler's equation:

$$\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} = -\frac{s_0^2}{n_0} \frac{\partial n}{\partial x} - \frac{v}{\tau} \quad (7)$$

Beyond of "gradual channel" approximation we have to solve Poisson equation to determine electron density in FETs channel. Let consider two gate electrodes at the distance d_1 and d_2 above and below the channel. The gate electrodes are assumed to be at the same potential. The case of $d_2 \rightarrow \infty$ corresponds to FET structure while $d_2 \sim d_1$ corresponds to the three terminal Junction FET (JFET) structure. The electrostatic constants are ε_1 and ε_2 above and below the channel correspondingly. For an infinitely long channel we can write the projection of eq. (4) in the x-y plane in an integral form:

$$U(x, z=0) = \int K(x') \delta n(x-x') dx' \quad (8)$$

The kernel K can be determined by the infinite system of gate images of the 2D charge distribution. Expanding $\delta n(x-x')$ in powers of x' we obtain a "gradual channel" approximation from a zero order term. The next non vanishing terms comes from the second order in the expansion, and Euler's equation (7) will be rewritten in form:

$$\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} = -\frac{s_0^2}{n_0} \left(\frac{\partial n}{\partial x} + L^2 \beta \frac{\partial^3 n}{\partial x^3} \right) - \frac{v}{\tau} \quad (9)$$

$$\text{where } \beta = \frac{d_1 d_2}{3 L^2} \frac{d_1 \varepsilon_1 + d_2 \varepsilon_2}{d_1 \varepsilon_2 + d_2 \varepsilon_1}$$

The expansion only works if both d_1 and d_2 are finite as compared to the wave-length of the density fluctuations.

In our investigations we studied the dynamic of electron fluid in bounded system solving the differential equations (6), (7), and (9) with continuity equation (1).

NUMERICAL STUDY.

The systems of partial differential equations, which we are studied, are nonlinear and can not be solved analytically. This non-linearity leads to shock waves creation and propagation in the channel. Various numerical methods has been developed in hydrodynamics to study flows containing shock waves. We use Lax - Wendroff numerical method. The relevant discussions of the stability of this numerical scheme can be found in [7, 8]. We adapted the

Lax - Wendroff method to the case of one - dimensional flow of electrons fluid in a systems with two boundaries and considered different sets of boundary conditions.

1.TIME INDEPENDENT BOUNDARY CONDITIONS.

It was shown [2] that in infinite region for various initial distributions of velocity (one shock wave, or infinite series of shock waves with triangular velocity profile) amplitude of shock wave diminishes asymptotically with time as $t^{-1/2}$ or t^{-1} respectively. It is of significant interest to determine the evolution of the amplitude of a shock wave with time t when it propagates in restricted region (like FET), reflecting from boundaries. But it can not been done analytically. We investigated this problem by numerical solution of system of differential equations (1), (6) for case $\gamma = 0$ [9].

Open circuit boundary conditions. These boundary conditions are the conditions of zero velocity at the source and drain end of the FET channel:

$$v(0,t) = v(L,t) = 0 \quad (10)$$

and we choose the following initial conditions:

$$n(x,0) = n_0 (1 + A \cos \pi x/L), \quad v(x,0) = 0 \quad (11)$$

where A is a dimensionless amplitude. The calculations show that the shock wave is formed in FET channel after a short time $t < T$, where characteristic time $T = L/s_0$. The density of electrons has a sharp step-like shape, and the velocity distribution has a triangular form. After the initial profile is transformed into a propagating shock wave the flow is a sequence of reflections of one shock wave whose amplitude decays with time as t^{-1} , see Fig. 1, curve (a). The time interval between two reflections is exactly $T = L/s_0$ even after many reflections. It means that instability moves with plasma wave velocity s_0 . The decay of shocks is related to energy dissipation at the shock front [2]. The particular law of decay depends on the boundary conditions and triangular form of velocity distribution.

Constant electric potential boundary conditions. These boundary conditions are given by $U(0,t) = U(L,t) = U_0$. In the "gradual channel" approximation these are replaced by

$$n(0,t) = n(L,t) = n_0. \quad (12)$$

We choose the following initial conditions:

$$n(x,0) = n_0 (1 + A \sin \pi x/L), \quad v(x,0) = 0 \quad (13)$$

After some transient time interval the two compression waves develop shocks propagating toward two boundaries. After the shock fronts reach the boundaries at $x=0$ and L the profile changes into two continuous waves in which the density $n(x,t)$ is larger than equilibrium value n_0 . The density profile then changes to the one in which n is smaller than n_0 and then into two compression waves propagating toward the middle of the channel. Two shock fronts develop, propagating toward each other. Upon "colliding" at $x=L/2$ the wave transforms into two shocks propagating toward the boundaries. This sequence of profile transformations repeats after each time interval $2T$. We checked that a choice of higher harmonics in the initial conditions leads to the same profile at time $t > T$. The magnitude of the waves, defined for this case as the maximum deviation in the interval $[0,L]$ from the equilibrium values of $n=n_0$ for the density and $v=0$ for the velocity, decreases with time. The envelope of the magnitude's time dependence is shown in Fig. 1, curve (b). At large times the decay is much slower than for the previous set of boundary conditions. We find that asymptotically the shock's amplitude decays slower than $t^{-1/2}$. Under this boundary conditions the shock waves are propagating in channel only part of each period $2T$. This is one of the reason of such slow decay.

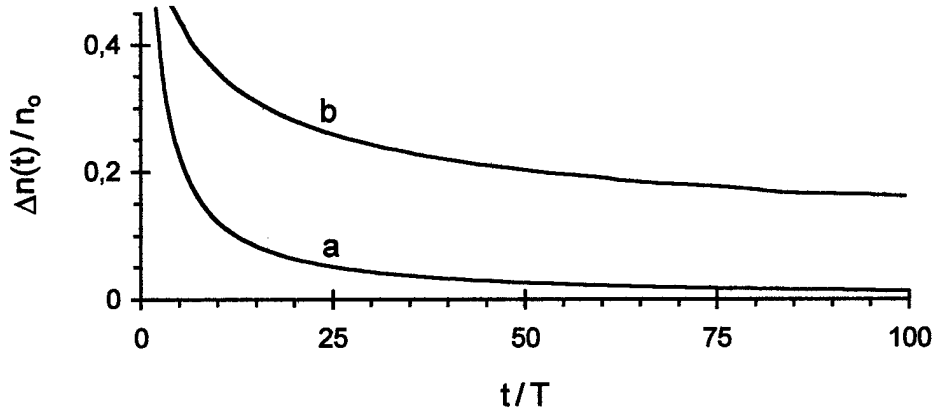


Fig.1. (a) The magnitude of the shock as a function of time for open circuit boundary conditions. It is defined as a difference of the density values behind and in front of the shock. At large times it decays as t^{-1} . (b) The envelope of the amplitude of the shock wave as a function of time for the constant potential boundary conditions. In this case the shock wave amplitude is defined as an absolute value of the maximum deviation from the equilibrium density n_0 .

Dispersion. If the distance between channel and gate electrode is not small with respect to the wave length of the density fluctuation, dispersion term may be important. We analyzed the effects of the non-linear dispersion of plasma waves for JFET structure (in case $\gamma=0$) [5]. The principal equations are the equation of continuity (1) and Euler's equation (9). We considered both of boundary conditions: open circuit boundary conditions

$$v(x=0, t) = v(x=L, t) = 0$$

$$\left. \frac{\partial n(x, t)}{\partial x} \right|_{x=0} = \left. \frac{\partial n(x, t)}{\partial x} \right|_{x=L} = 0 \quad (14)$$

and constant electric potential boundary conditions

$$n(x=0, t) = n(x=L, t) = n_0$$

$$\left. \frac{\partial n(x, t)}{\partial x} \right|_{x=0} = \left. \frac{\partial n(x, t)}{\partial x} \right|_{x=L} = 0 \quad (15)$$

For example, in case (15) a small non-zero value of β turns a two-step sock wave into a smooth shape at large times. The decay law of amplitude of the wave is slower than in case $\beta = 0$.

The system of partial differential equations (1), (9) did not allow us to investigate the role of dispersion term for big values of dimensionless coefficient β ($\beta > 10^{-5}$). In this case we have to solve integro-differential equations (1), (2), which will be a next stage of our further investigations.

2. RESPONSE TO HARMONIC SIGNALS.

The evolution of electron density and velocity in FETs channel are described by the nonlinear system of partial differential equations. In section 1 it was shown that this non linearity leads to a shock wave creation. But if the boundary conditions are time independent the amplitude of shock wave decay with time even in case $\gamma=0$ because of energy dissipation at the shock front. On the next step of our investigation we study the response of electron fluid in FETs channel when periodically boundary condition are applied at the source and the drain [10, 11] or only at the source of channel [4, 12]. It was shown that such "open" systems may be used for creating a new type of devices. The basic differential equations are the equation of continuity (1) and Euler's equation (7).

Self-consistent voltages. The hydrodynamic analysis shows that the plasma oscillations may become unstable when the electron density variations in the channel are not small. Then new nonlinear effects appear in the device response. Here we show that the impact of the plasma behavior may be felt at the frequencies much lower than the fundamental plasma resonance frequency ω_0 and the input of plasma oscillations will appear in the microwave range. Let consider the boundary conditions at the source and the drain of channel as follows: $U(0,t)=U_0+U_s\cos(\omega_s t)$, $U(L,t)=U_0+U_d\cos(\omega_d t)$. In the "gradual channel" approximation these are replaced by

$$n(0,t) = n_0 \left[1 + A_s \cos(\omega_s t) \right], \quad n(L,t) = n_0 \left[1 + A_d \cos(\omega_d t) \right] \quad (16)$$

Here ω_s , A_s and ω_d , A_d are frequencies and dimensionless amplitudes at the source and at the drain of conduction channel. In our next investigations we will refer to frequency f defined by $\omega=2\pi f$. We choose following initial conditions:

$$n(x,0) = n_0 \left[1 + (A_d - A_s) \frac{x}{L} + A_s \right], \quad v(x,0) = 0. \quad (17)$$

The response of 2D electrons plasma can be characterized by the induced currents at the source and drain of FET channel. Here we consider only the source current density obtained as $j_s(t)=en(0,t)v(0,t)$. As a first example we take the following values of parameters: $U_s/U_0 = U_d/U_0 = 0.1$, $\omega_s/\omega_0 = 0.01$, $\omega_d/\omega_0 = 0.03$, $\gamma = 0.1$, and $U_0 = 1V$. These values can be obtained for mobility $\mu=10 \text{ m}^2/Vs$ and channel length $L=0.61 \text{ } \mu\text{m}$. Then $s_0=1.62 \cdot 10^8 \text{ cm/sec}$, characteristic time $T=0.376 \cdot 10^{-12}s$, $f_s = 4.22 \text{ GHz}$ and $f_d = 12.66 \text{ GHz}$. The current per unit width of the channel is shown in Fig.2, solid curve. For comparison we also showed the solution of the linearized equations, broken curve, for the same values of parameters.

For the larger values of ac amplitudes or frequencies or for the smaller values of the friction coefficient the density profile will show propagating waves. An example in Fig.3 corresponds to $\gamma = 0.001$ and the same amplitudes and frequencies as in Fig.2. In this case the shock wave propagates in the conduction channel. In Figures 4 and 5 we show the density profiles for the parameter values of Fig.3, at different stages of one cycle. In Fig.5 the shock front propagates much faster than in Fig.4, and the profile can be described as a shock wave undergoing successive reflections at the boundaries $x=0$ and $x=L$. In order to reduce the numerical artifact of rapid oscillations behind the shock front we added a small viscosity term in the difference scheme.

The simplest measure of the nonlinear effects in the device response is the "zero harmonic" in the source current density, obtained as a time cycle average $\langle j_s(t) \rangle$. This is shown in Fig.6 as a function of the ac drain amplitude U_d for $U_0 = 1V$, $U_s = 0.1 V$, friction parameter $\gamma = 0.01$, for equal frequencies at the source and drain terminals, $\omega_s/\omega_0 = 0.01$ for curve 1 and $\omega_s/\omega_0 = 0.1$ for curve 2. We see that due to the nonlinear response of the 2D plasma a substantial constant current component can be induced at the source and drain terminals by the harmonic ac signals.

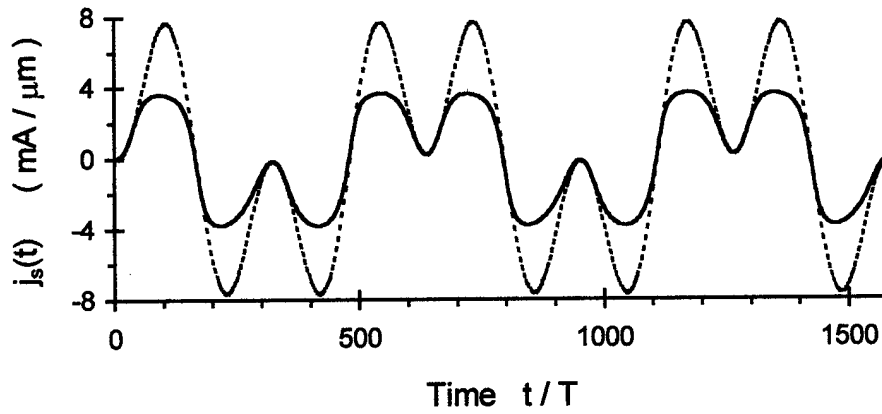


Fig.2. Source current density $j_s(t)$ as a function of time. The time is shown in units of the characteristic time scale T defined as ratio of channel length L to plasmon velocity s_0 . The average gate voltage swing $U_0=1V$, the source and drain ac amplitudes are $U_s=U_d=0.1U_0$, ac frequencies are given by $\omega_s/\omega_0=0.01$, $\omega_d/\omega_0=0.03$ in units of characteristic plasma frequency defined as $\omega_0=2\pi/T$. The value of friction parameter is $\gamma=0.1$. The solid curve is obtained from the numerical solution of the nonlinear equations (7) and (1). The dashed curve is for the linear approximation of the same system.

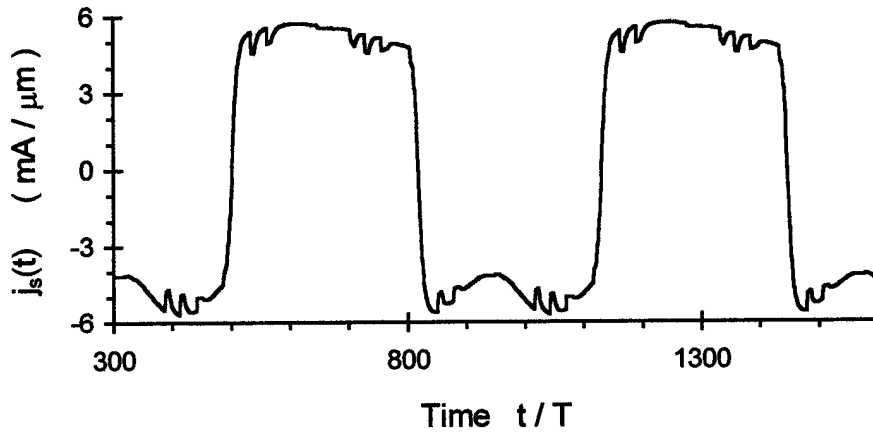


Fig.3. Source current density $j_s(t)$ as a function of time. Time is shown in units of characteristic time scale defined as in Fig. 2. Friction parameter $\gamma=0.001$. Amplitudes and frequencies of applied signals are given in units of average gate voltage swing U_0 and characteristic plasma frequency ω_0 : $U_s = U_d = 0.1U_0$, $\omega_s = 0.01\omega_0$, $\omega_d = 0.03\omega_0$.

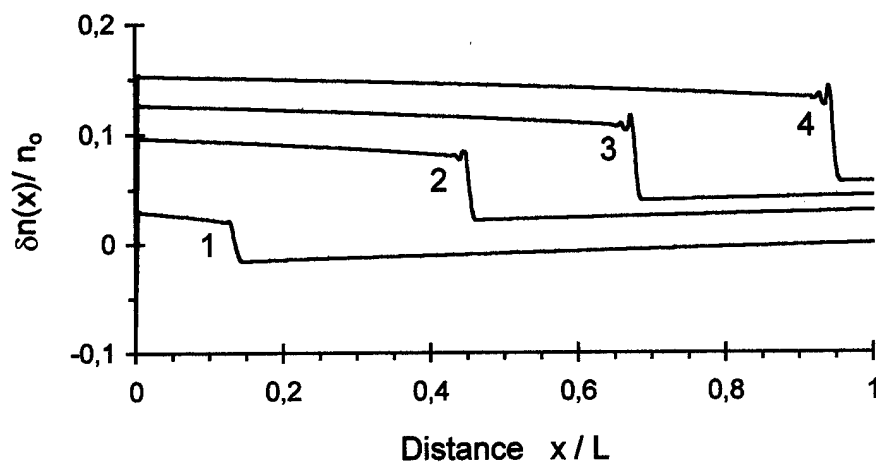


Fig.4. Density profiles corresponding to the case of Fig. 3. The electron density variation, defined as $\delta n(x) = n(x) - n_0$, is plotted in units of the equilibrium density n_0 at different times as a function of x/L , where L is channel length. Time interval is corresponded to rapid oscillations on the bottom of the source current in Fig. 3; the values of t/T are (1) 995, (2) 1005, (3) 1010, (4) 1015. At each of this times the profile is a compression wave containing a shock front propagating from the source to the drain.

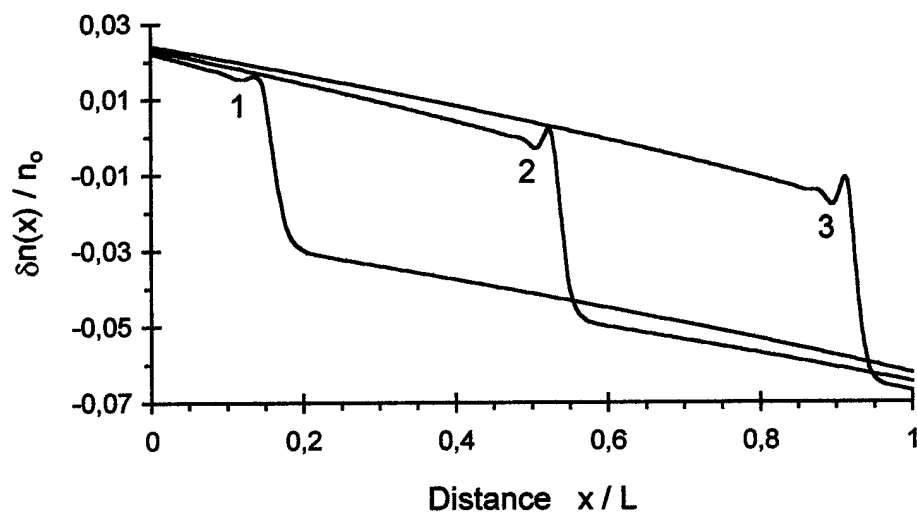


Fig.5. Density profiles corresponding to the case of Fig. 3. The electron density variation, defined as $\delta n(x) = n(x) - n_0$, is plotted in units of the equilibrium density n_0 at different times as a function of x/L . Time interval is corresponded to the rapid rise of the source current in Fig. 3; the values of t/T are (1) 1122, (2) 1123, (3) 1124. The shock wave propagates from the source to the drain, fast enough to undergo successive reflections from boundaries during the corresponding time interval.

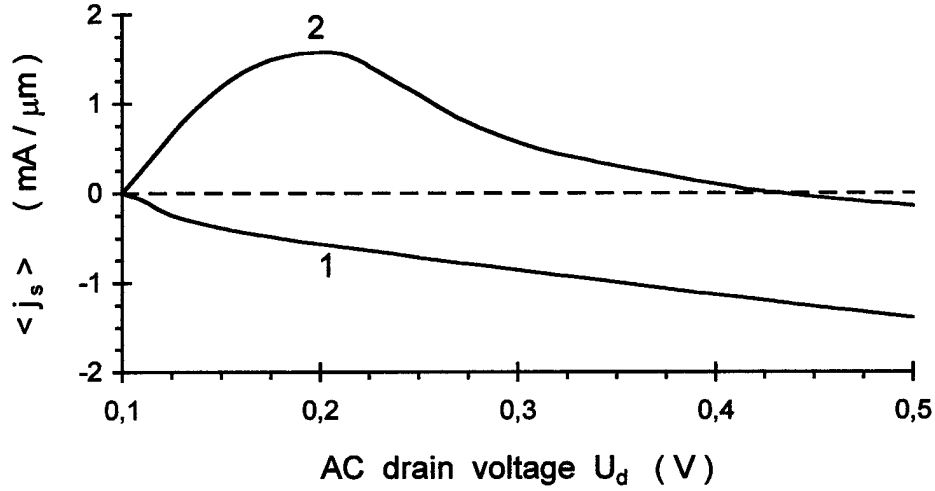


Fig.6. Induced dc component of the source current density $\langle j_s \rangle$ in GaAs HEMT as a function of the ac amplitude of the applied drain voltage in the case of equal frequencies of the source and drain potentials. The gate voltage $U_0=1\text{V}$, source voltage ac amplitude $U_s=0.1U_0$, friction parameter $\gamma=0.01$, the frequencies of the applied ac signals in units of characteristic plasma frequency ω_0 are: (1) $\omega_s=\omega_d=0.01\omega_0$, (2) $\omega_s=\omega_d=0.1\omega_0$.

Plasma wave detector. A plasma wave detector of terahertz radiation is expected to have a very large responsivity. The analytical theory [4] predicts that it can exceed typical responsivities of Schottky diode detectors by several orders of magnitude. However, the analytical theory is only valid for a small signal excitation U_s/U_0 and can not predict the detector dynamic range, which is determined by the responsivity dependence on the U_s/U_0 . We compute the dependencies of the detector response on the excitation level for different gate length L , and electron mobilities μ , and compare our results with analytical theory.

The boundary conditions for the FET channel (for the detector mode of operation) are $U(0,t) = U_0 + U_s \cos(\omega_s t)$, $j(L,t)=0$, or in "gradual channel" approximation

$$n(0,t) = n_0 \left[1 + A_s \cos(\omega_s t) \right], \quad j(L,t) = 0 \quad (18)$$

where dimensionless amplitude $A_s = U_s/U_0$. We chose the following initial conditions:

$$n(x,0) = n_0 \left[1 + A_s (1 - x/L) \right], \quad v(x,0) = 0. \quad (19)$$

We calculated the mean value of drain-to-source voltage U_{ds} , which in "gradual channel" approximation can be written as follows:

$$U_{ds} = \frac{e}{CT} \int_0^T n(x=L,t) dt \quad (20)$$

The calculations were done for GaAs ($m=0.067m_0$), for various gate length $L = 0.1, 0.5, 2.0, 5.0 \mu\text{m}$ and electron mobilities $\mu = 0.2, 0.8, 3.0, 6.0, 10.0 \text{ m}^2/\text{Vs}$. Fig. 7 compares the results of the numerical calculations with the predictions of the analytical theory [4]. As can be seen from the figure the agreement is good enough at small values of the ac signal amplitude. For big values of (U_s/U_0) the detector response becomes a sublinear function $(U_s/U_0)^2$. This corresponds to a dramatic drop in the detector responsivity. For such big values of excitation level the electron density variation is not small, the shock wave is created and propagated in the conduction channel. This leads to a smoothing of difference between mean electron density at the source and at the drain terminals.

The analytical theory predicts that the peak responsivity increases with an increase in the low field mobility. Our numerical simulations show that such an increase is limited to a small signal excitation. This is clearly illustrated by Fig. 8, which shows the computed detector response for the electron mobilities of $10 \text{ m}^2/\text{Vs}$, $6 \text{ m}^2/\text{Vs}$, $3 \text{ m}^2/\text{Vs}$, $0.8 \text{ m}^2/\text{Vs}$, and $0.2 \text{ m}^2/\text{Vs}$. As can be seen from the figure, at large signal amplitude, the effect of the electron mobility is greatly diminished.

The deviation from the analytical theory also depends on the dimensionless friction γ , see Fig. 9. One can see that the difference between analytical theory and our calculations decreases with an increase of γ . This is also connected with creation and propagation of shock wave in channel. For $\gamma > 1$ the shock wave is damped and computer calculation are in good agreement with prediction of analytical theory.

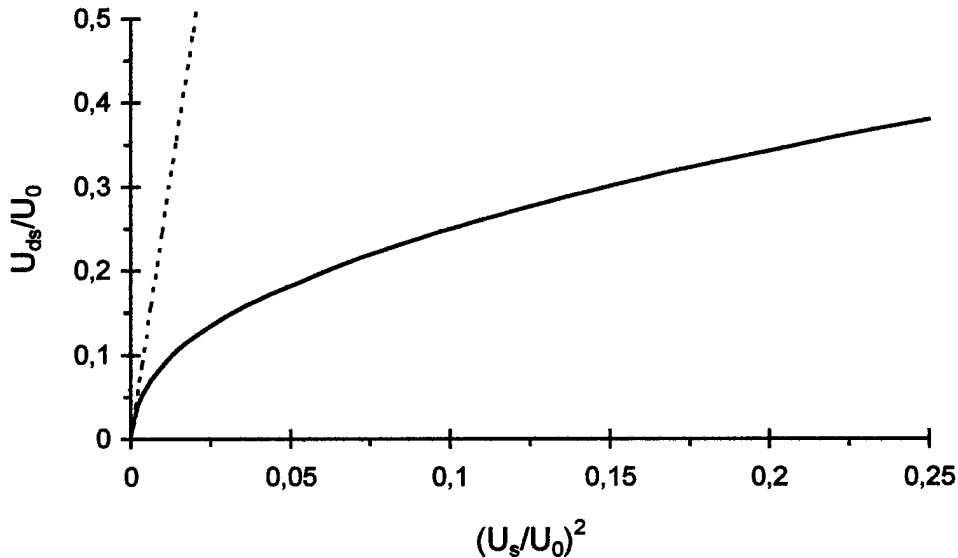


Fig.7. Detector response versus signal amplitude. Comparison of numerical calculations (solid line) with the analytical theory (dashed line). The average gate voltage swing $U_0 = 1\text{V}$, electron mobility $\mu = 0.8 \text{ m}^2/\text{Vs}$, gate length $L = 0.1 \mu\text{m}$.

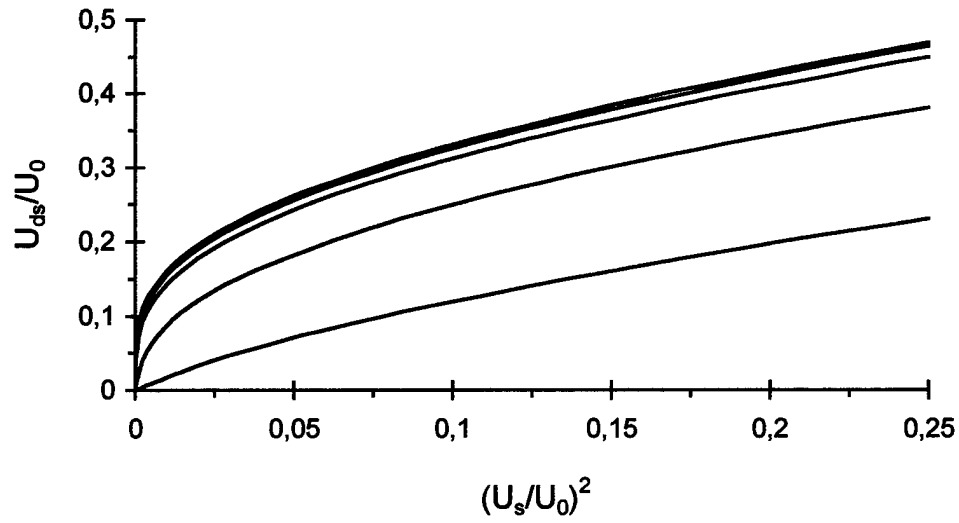


Fig.8. Detector response versus signal amplitude for different values of low field mobility. The curves (from the top to the bottom) are for the electron mobilities of $10 \text{ m}^2/\text{Vs}$, $6 \text{ m}^2/\text{Vs}$, $3 \text{ m}^2/\text{Vs}$, $0.8 \text{ m}^2/\text{Vs}$, $0.2 \text{ m}^2/\text{Vs}$, and for gate length $L=0.1 \text{ μm}$.

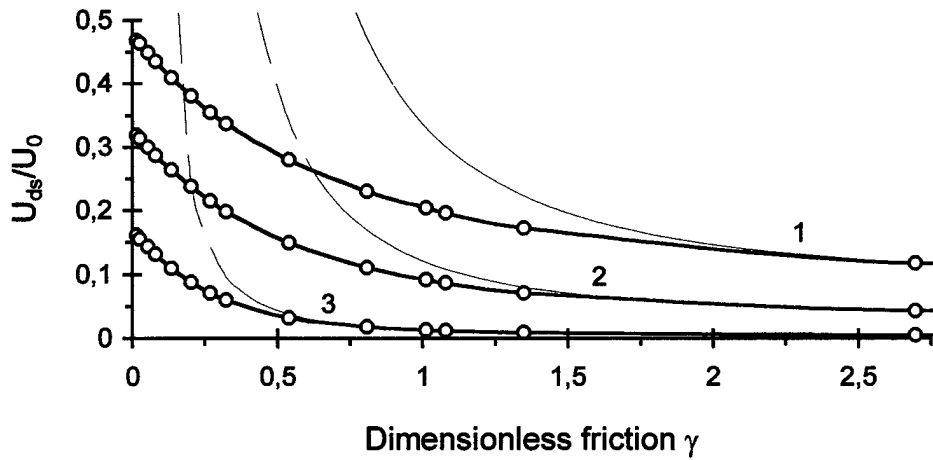


Fig.9. Comparison of computed detector response as a function of dimensionless friction γ , with analytical results (dashed lines) for three values of the ac signal amplitude: $U_s/U_0 = 0.5$ (curves 1), $U_s/U_0 = 0.3$ (curves 2), $U_s/U_0 = 0.1$ (curves 3).

CONCLUSION.

In this report we described the behavior of shock waves in FETs structures when various boundary conditions are applied at the source and at the drain of conduction channel.

We studied the strongly nonlinear regime of a plasma oscillations. The propagation and decay of shock-like waves under time independent boundary conditions was investigated. We also considered effects of the small nonlinear dispersion on plasma waves shape in bounded systems. This extends the hydrodynamic theory of FET beyond the "gradual channel" approximation.

It was shown that the hydrodynamic model of electron transport provides a simple way to study the interior dynamics of submicron devices at large carrier densities. Using this approach we find that nonlinear plasma oscillations may affect the device response at frequencies much lower than the characteristic, or resonant, plasma frequency. The nonlinear effects are noticeable when the boundary conditions are asymmetric, i.e. when a frequency, or amplitude, shift exists between ac signals applied at the drain and source terminals of FET. Any of these asymmetries may lead to the appearance of nonlinear hydrodynamic effects in the conduction channel, such as formation and propagation of shock-like plasma waves. These are accompanied by nonlinear effects in the device response to harmonic signals, which generate both dc and higher harmonics in the terminal current spectrum. The induced dc current component can in principle be measured by using standard microwave circuits.

Based on the numerical solution of the basic hydrodynamic equations we computed the dependencies of the detector responsivity on the excitation level for different gate length and electron mobilities. Our results show that the dynamic range of these plasma wave electronic devices is determined by the creation and propagation of shock waves in the conduction channel. As the amplitude of the ac signal applied to the detector increase, the detector responsivity decreases.

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